MICROMACHINED STIMULATING MICROELECTRODE ARRAYS

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MICROMACHINED STIMULATING MICROELECTRODE ARRAYS

Summary

This contract seeks to develop a family of thin-film stimulating arrays for use in neural prostheses. STIM-2B/-3B are two- and three-dimensional arrays of stimulating sites on 400μm centers. The probes have four channels and 64-sites. Any selected site can be used for either recording or stimulation. Current generation is off-chip. This probe design has now been completed, with 3D arrays of the STIM-3B probes formed in arrays as large as 1024 sites (256 shanks and 64 parallel data channels, accessible over just eleven external leads). The high-end probes STIM-2/-3 are similar except they use on-chip current generation via 8-bit digital to analog converters. They are accessible over seven external leads.

During the past quarter, work has concentrated in three areas. We have designed and had fabricated at MOSIS a two-channel sixteen-site version of the active probe, STIM-2. This chip contains improved DAC current drivers as well as full self-test circuitry. The probe was returned from MOSIS and is currently in test. The digital input circuit blocks, the DAC circuitry, the anodic bias generator, and the associated self-test circuitry is all fully functional. A detailed comparison of the measured performance with the design simulations is underway. We have also designed a new four-channel 32-site version of STIM-2/-3. This probe has new DAC circuits which are considerably smaller than their predecessors at the cost of some absolute accuracy in the current settings. These probes have been realized in both two-dimensional acute and three-dimensional chronic (platform) versions. To minimize the height of the probes above the platform, we are experimenting with fold-down gold beams in place of silicon cables. The silicon cables have the advantage of being fully insulated on-chip but cannot bend through sharp angles without breaking. The gold beams can be bent at right angles and hence can be shorter and more robust but at the expense of being subject to leakage. However, in a platform situation, these beams will be inside the protective cap and thus not exposed to extracellular fluids. They can also be potted in silicone so that leakage is not expected to be a problem, especially in stimulating situations. Full results from the MOSIS chip and initial results from the STIM-2/-3 probes should be available next term.

We have also designed a two-channel 16-site active stimulating probe with an on-chip wireless link. This probe is thus completely self-contained, including current drivers, input circuitry, power generation, and wireless interface. If wired, the probe can be operated over a two-wire line. The probe is organized as four four-site shanks. Sites can be programmed as high-impedance, driven to VCC, operated in current sinking mode, or tied to an analog access line. The probe uses an 18b input control word. Probe addresses in multi-probe configurations are set by laser trimming of links. The wireless interface uses an FSK data recovery block that achieves data rates above 1Mbps from the 4MHz carrier. The power block uses a CMOS full-wave rectifier with power-on-reset for the input circuitry. A fold-down version of this probe is included to minimize the height

of the structure above the cortex. The shanks are 3.1mm long by 60µm wide spaced 250µm apart. These probes should be realized before the end of the year.

MICROMACHINED STIMULATING MICROELECTRODE ARRAYS

1. Introduction

The goal of this contract is the development of active multi-channel arrays of stimulating electrodes suitable for studies of neural information processing at the cellular level and for a variety of closed-loop neural prostheses. The probes should be able to enter neural tissue with minimal disturbance to the neural networks there and deliver highly-controlled (spatially and temporally) charge waveforms to the tissue on a chronic basis. The probes consist of several thin-film conductors supported on a micromachined silicon substrate and insulated from it and from the surrounding electrolyte by silicon dioxide and silicon nitride dielectric films. The stimulating sites are activated iridium, defined photolithographically using a lift-off process. Passive probes having a variety of site sizes and shank configurations have been fabricated successfully in past contracts and have been distributed to a number of research organizations nationally for evaluation in many different research preparations. For chronic use, the biggest problem associated with these passive stimulating probes concerns their leads, which must interface the probe to the outside world. Even using silicon-substrate ribbon cables, the number of allowable interconnects is necessarily limited, and yet a great many stimulating sites are ultimately desirable in order to achieve high spatial localization of the stimulus currents.

The integration of signal processing electronics on the rear of the probe substrate (creating an "active" probe) allows the use of serial digital input data that can be de-multiplexed on the probe to provide access to a large number of stimulating sites from a very few leads. Our goal in this area is to develop a family of active probes capable of chronic implantation in tissue. For such probes, the digital input data must be translated on the probe into per-channel current amplitudes that are then applied to tissue through the sites. Such probes generally require five external leads, virtually independent of the number of sites used. As discussed in previous reports, we have designed a series of active probes containing CMOS signal processing electronics. Two of these probes have been completed and are designated as STIM-1A and STIM-1B. A third probe, STIM-2, is now beginning a final iteration and is a second-generation version of our original high-end first-generation design, STIM-1. All three probes provide 8-bit resolution in digitally setting the per-channel current amplitudes. STIM-1A and -1B offer a biphasic range using ±5V supplies from 0μA to ±254μA with a resolution of 2μA, while STIM-2 has a range from 0 to ±127μA with a resolution of 1μA. STIM-2 offers the ability to select 8 of 64 electrode sites and to drive these sites independently and in parallel, while STIM-1A allows only 2 of 16 sites to be active at a time (bipolar operation). STIM-IB is a monopolar probe, which allows the user to guide an externally-provided current to any one of 16 sites as selected by the digital input address. The high-end STIM-2 contains provisions for numerous safety checks and for features such as remote impedance testing in addition to its normal operating modes. It also offers the option of being able to record from any one of the selected sites in addition to stimulation. It will be the backbone of a multi-probe three-dimensional (3D) 1024-site array (STIM-3) now in development. A

new probe, STIM-2B, has recently been added to this set. It offers 64-site capability with off-chip generation of the stimulus currents for four separate channels. These channels are organized in four groups so that each current can be directed to any of the 16 sites in its group. Each selected channel can be programmed for either stimulation or recording. On-chip recording amplifiers offer a gain of 50; alternatively, the neural activity can be recorded using off-chip amplifiers interfaced through the normal stimulating channels. This probe is available in both 2D and 3D versions (as STIM-2B/3B) and is now being used in-vivo.

During the past quarter, we have focused work testing foundry version of the circuitry for STIM-2/-3 and on designing a new version of the monolithic probe that is now in fabrication. We have also designed a 16-site active probe with full drive circuitry on-chip, including the wireless link. The results of these efforts are described more fully in the sections below.

2. STIM-2/3: A Multiplexed Stimulating Probe with On-Chip Current Generation

During the past quarter, the chip designed to implement two complete channels serving 16 sites was returned from fabrication at MOSIS. Due to an unexpected re-fabrication of this run at MOSIS to correct fabrication problems there, it was delivered a month later than originally scheduled. A picture of the chip, which measures 2mm x 2mm, is shown in Fig. 1. Test structures not included, the circuitry takes an area of 1.9mm by 1.5mm. The chip is currently under testing and the some test results are discussed as follows.

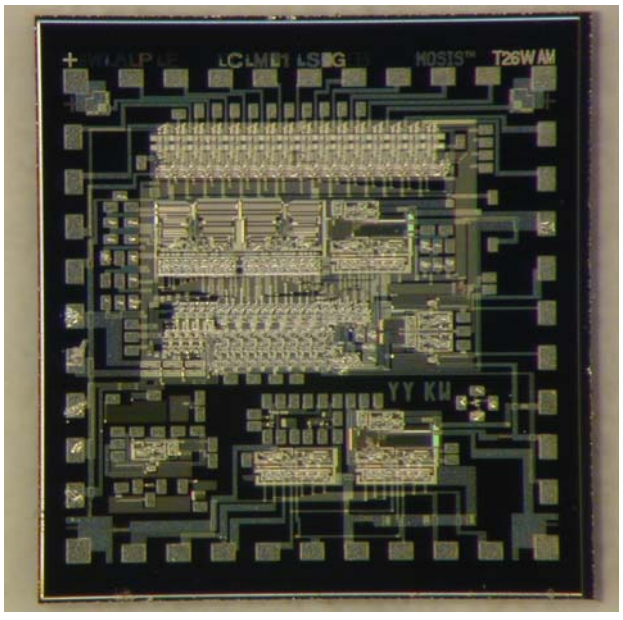


Fig. 1: Picture of the MOSIS chip implementing the stimulating interface for two channels serving 16 sites. This chip is therefore one-quarter of the full STIM-2 system.

The digital circuit block implementing the input shift register and latches was first tested. Figure 3 shows the input signals and the output waveform from the 8-bit shift-register. The input data string is "11001101 00000000". According to the data, the chip should operate in the "stimulating mode", with the first channel and fifth site assigned to this channel selected. Figure 3 shows the waveforms obtained from corresponding test points. The digital circuit works as expected.

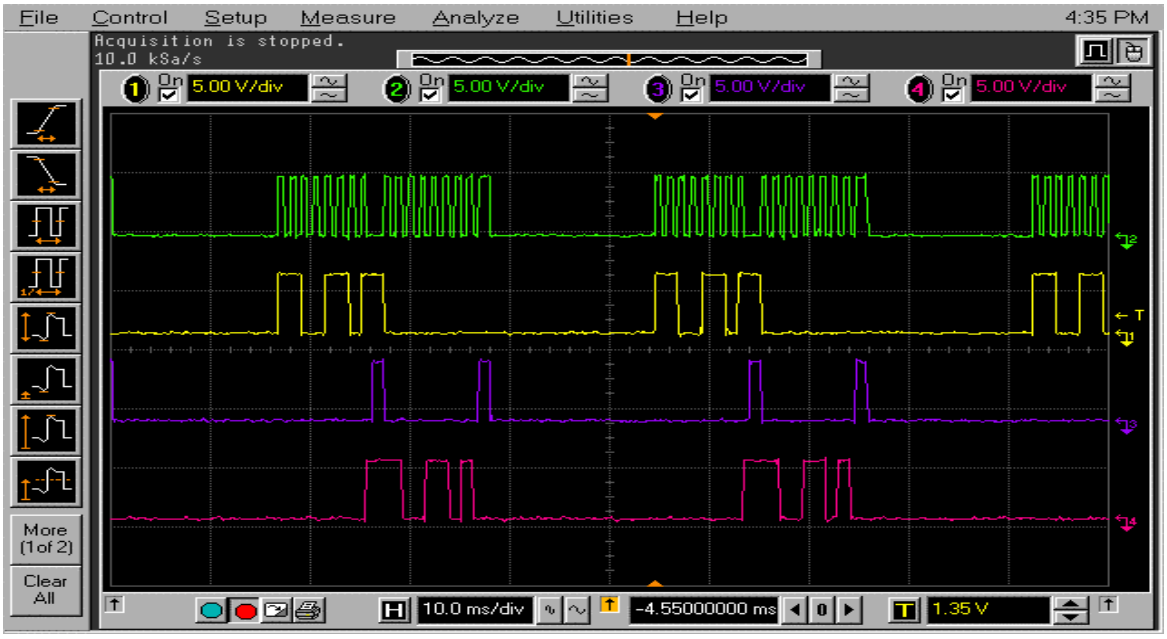


Fig. 2: From top to bottom, this oscilloscope output shows the input clock, input data, strobe signals and the output from the shift register, selecting channel one and site five.

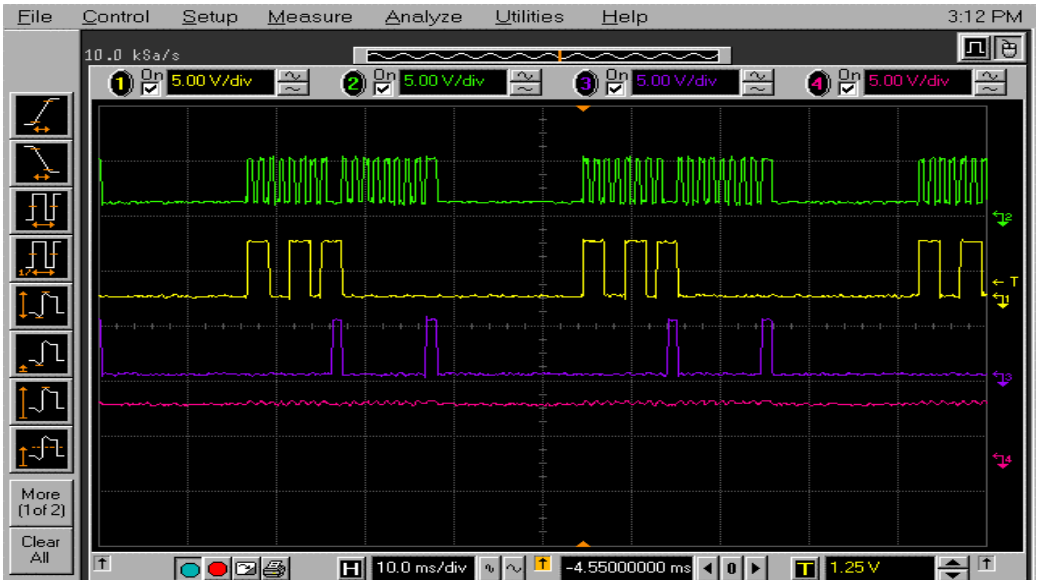


Fig. 3: Test waveforms from the MOSIS chip. (a) input clock, data and strobe signals and the waveform on the stimulating-enable line.

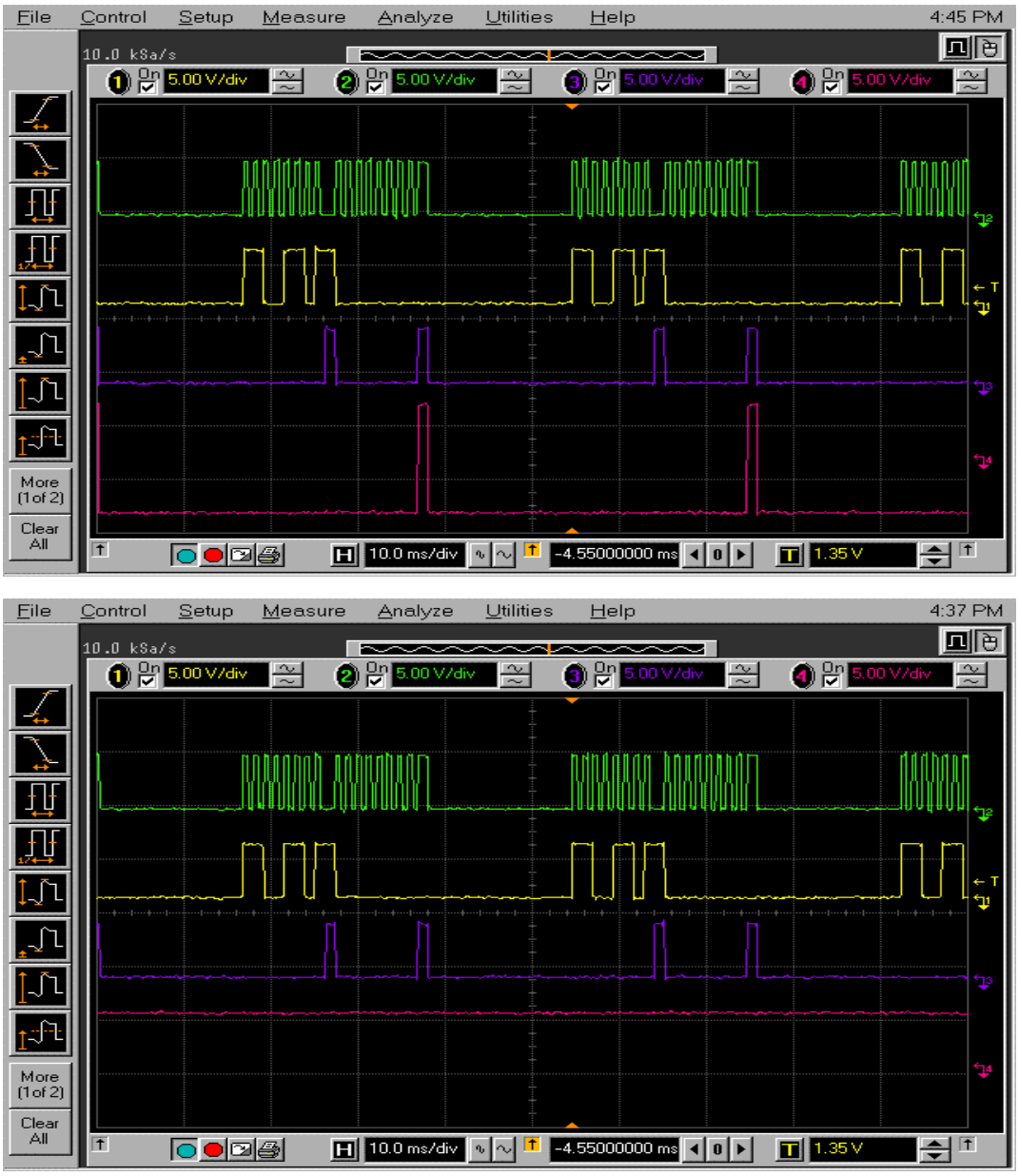


Fig. 3: Test waveforms from the MOSIS chip. (b) input signals and the channel #1 selection line logically "anded" with strobe signal; (c) input signals and waveform on the site#5 selection line

The DAC and anodic bias circuitry were then tested. Figure 4(a) shows the input square wave fed into the least significant bit of the DAC along with the output waveform across a 100kΩ resistor built on-chip. During the positive cycle of the input signal, a 1μA sink current was expected to flow across the resistor, i.e., a 100mV voltage should appear across it. During the negative cycle, a 1μA sourcing current should flow through

it, producing a minus 100mV voltage across the resistor. The measured waveform agrees with the expected result. In checking the anodic bias generation, the voltage across the resistor is fed into a unity gain source follower and is then taken off-chip. The output from the anodic bias generator is shown in Fig. 4 (b). This block is also fully functional.

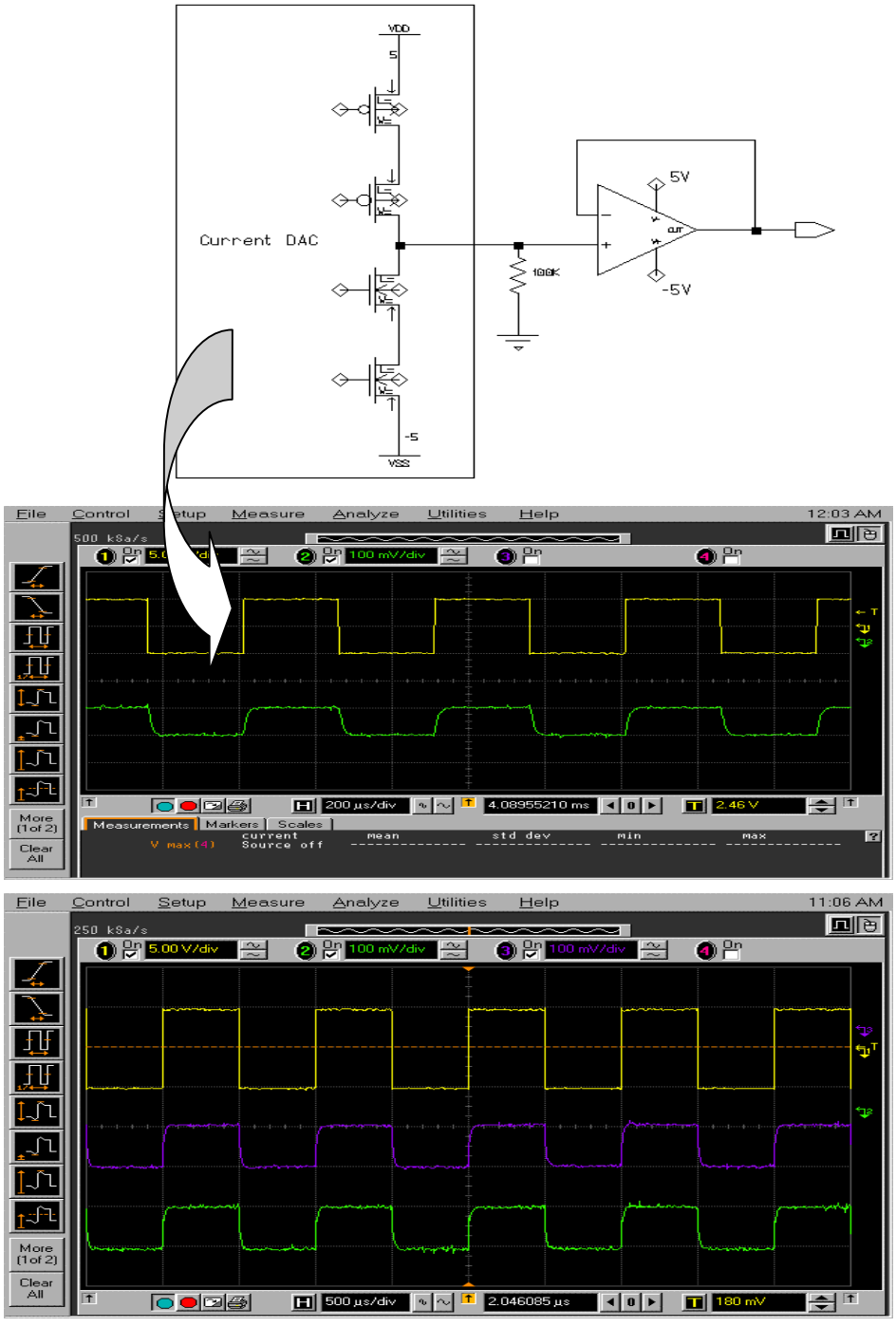


Fig. 4: Output waveform from the DAC and the anodic bias circuit. (a) input square wave and output across the 100kΩ resistor; (b) from the top to bottom is: input square wave, waveform across the resistor and output from the anodic bias.

Further testing is needed before the chip can be bonded with a passive probe and used as hybrid system. In the meantime, the design and layout of a modified version of STIM-3 has been finished. This new STIM-3 probe is fully self-testing but contains only 32 sites and four channels instead of the 64-sites and 8 channels of its predecessor. The idea here is to generate something smaller and more user friendly and something more suitable for testing and use in-vivo. Subsequently, the full 64-site probes based on the new circuitry will also be fabricated. Some new features are included in this run as follows.

1) To reduce the area of the backend circuitry, the DAC current generators no longer are based on the use of replicated unit transistors to build up the required currents with high accuracy. Instead, the current ratios are achieved by scaling the transistor sizes. This will affect the linearity of the DAC performance to some extent but saves area, and it is doubtful that absolute accuracy in setting the current levels is of great importance here.

2) A kT/q reference circuit is used to bias the DAC in order to make it less dependant on the power supply variations. The schematic is shown in Fig. 5. On the lower right is the startup circuit for the reference block.

3) In self-testing mode, the site connections (poly interconnect to the Ir/Ti sites) are tested by forcing a signal onto a specific site and measuring the output on the output data line as the signal goes through the site. Two different forcing signals are generated on-chip: AC and DC. In AC mode, to minimize signal feedthrough and any resulting errors, the input clock signal is frequency-divided by 2. This testing mode is easy to use, but if working in-vitro or in-vivo, the test signal will pass through the solution or tissue, possibly resulting in unwanted stimulation. In this case, a DC signal of 0.1V can be generated and used.

4) Two versions of the probe circuitry have been designed for this run: one version has two DACs and two amplifiers. This is actually a stimulating/recording combo. The same amplifier implemented in the recording probe PIA-2 is used here; the other has 2 DACs, 1 amplifier and a self-test block.

5) Four different probe configurations have been laid out as shown in Fig. 6. Both 2-D and 3-D probes with different interconnections between the backend and the shanks have been designed, and their use for low-profile multi-probe assemblieswill be characterized and compared. The probe circuit areas fold over flat against the platform, minimizing the height of the platform above the cortical surface. Both silicon and gold beams have been used for the folding portions. These probes are currently under fabrication and should be completed before the end of this year.

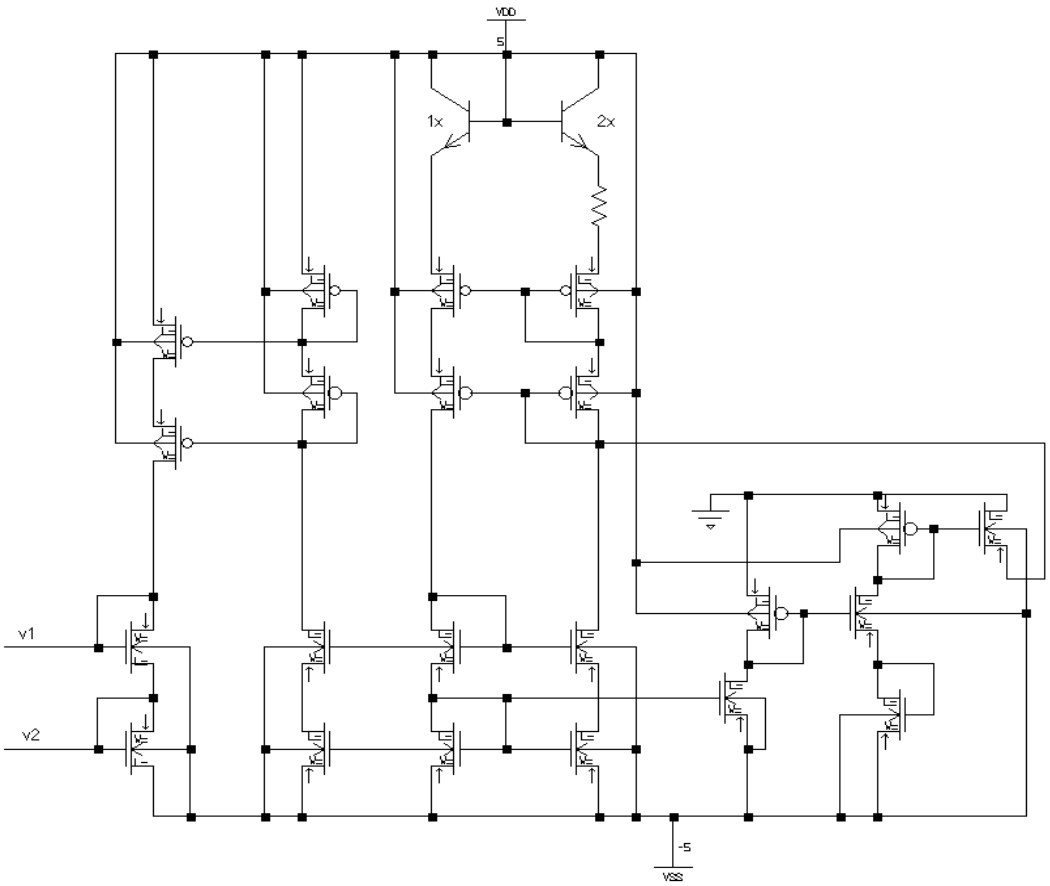
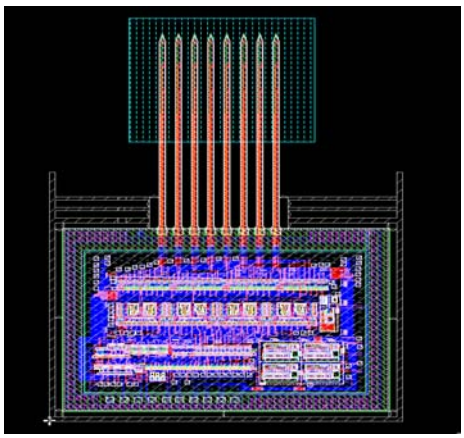
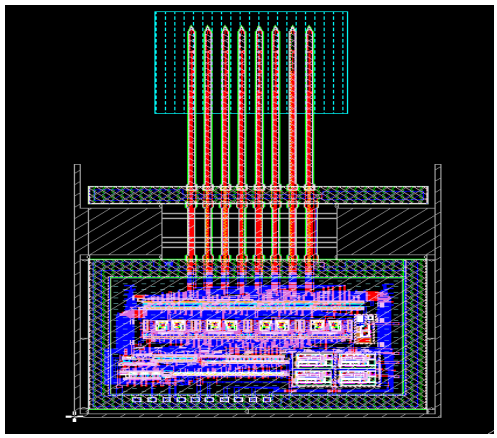


Fig. 5: Schematic of the kT/q DAC reference circuit

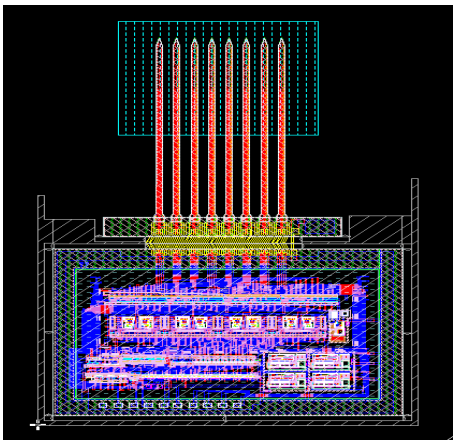


(a) 2-D probe

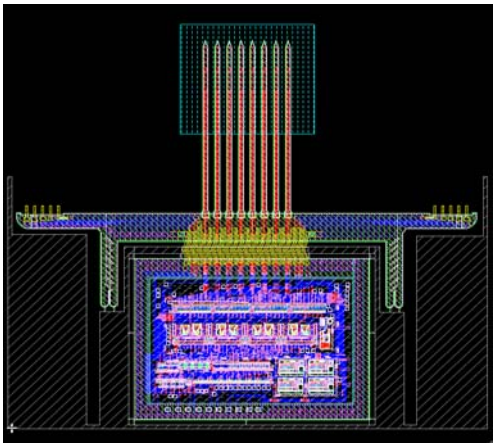


(b) 2-D probe with silicon ribbon cables as interconnections

Fig. 6: Various versions of the STIM-2/-3 probe designs: a) a 2D acute probe; b) a 2D probe having a circuit area that can fold over using silicon interconnect cables between the front end and the circuitry.



(c) 2-D probe with electro-plated gold beams as interconnections



(d) 3-D probe with gold beams as interconnections

Fig. 6: Various versions STIM-2/-3: c) a 2D acute probe with gold beams between the front-end and the circuitry; d) a 3D chronic probe rigged for platform mounting with gold fold-down beams.

3. A Wireless CNS Stimulating System

During the last quarter, we were able to operate individual blocks on the Interestim-1 chip successfully and according to our plan we were supposed to test the Interestim-2 individual blocks as well as verify the whole chip functionality during this quarter. However, the University of Michigan BiCMOS fabrication run was scheduled to kick off in September. Therefore, we decided to postpone the rest of our measurements until the next quarter and use our preliminary results from Interestim-1 and -2 as a basis for designing the next generation of the Interestim chips, Interestim-3, so it could be included in this fabrication run. Interestim-3 is a 16-channel wireless addressable stimulator, which is integrated into the back-end of an active micromachined probe and is equipped with full-wave CMOS rectifier and high data transfer rate demodulator circuits. Up to 64 of these addressable probes can share a single receiver tank circuit in a 1024-site wireless three-dimensional stimulating array. During the next quarter while our new designs are in fabrication, we will resume our measurements on the Interestim-1 and 2 chips. We are going to use functional chips in a larger system by putting together different components of a wireless stimulating microsystem such as the transmitter circuitry, receiver/transmitter coils, and a PC-based command generation station, which was partly done in the last quarter. This report continues on the schematic and layout design of the Interstim-3 microstimulating system.

Interestim-3 Block Diagram:

Design of Interestim-3 was based on the experience gained from the Interestim-1 and -2 chips. We also tried to reuse as many of the tested blocks and layouts as possible

in the new chip with minor modifications in order to improve their performance. The 16-channel wireless stimulator is an extension of the Interestim-2, our prototype 4-channel wireless stimulator, in addition to an address decoder. Figure 7 shows the overall block diagram of Interestim-3. Coil1 and coil2 are two nodes of the implantable tank circuit, and all of the parallel probes in a 3D array are connected to it. These are the only inputs of the entire implanted system no matter how many probes are used in parallel. Therefore, even if Interestim-3 is to be used in a hard-wired system, the number of transcutaneous wires has been reduced from 7 to only 2 wires compared to our previous active stimulating probes, the STIM series. Besides, since the two wires in this system carry a high frequency sinusoidal AC signal at 4MHz, passing through the skin is much safer than the STIM-2/-3 probe 7-wire system, which includes Vcc, Vss, and GND as DC interconnects.

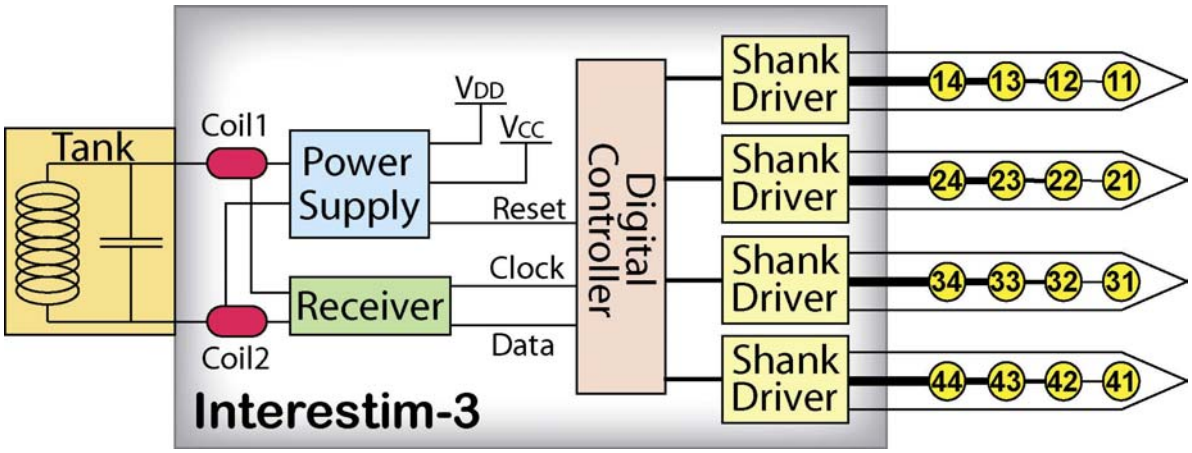


Fig. 7: The Interestim-3 overall block diagram

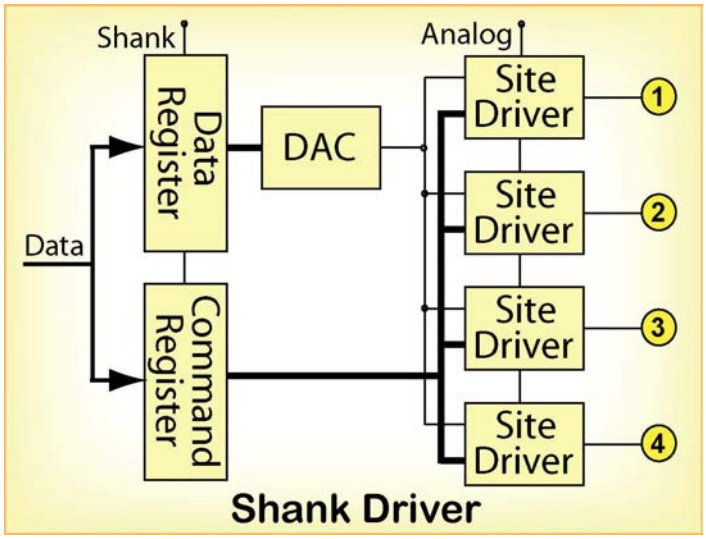


Fig. 8: The shank driver block diagram

Each Interestim-3 probe has four shanks and each shank has four stimulating sites on it, controlled by an individual shank driver block. A more detailed diagram of the shank driver block is shown in Fig. 8. This block is very similar to what we have in Interestim-2; in Interestim-3 every shank is driven by an individual Interestim-2 circuit. There are two 8-bit registers in every shank driver. The command register keeps the configuration of the sites, whether they are involved in a biphasic-bipolar stimulation, at high impedance, or connected to the common analog line that passes through all of the site driver blocks. Every site has an individual site driver circuit, shown in Fig. 9, controlled by two bits of the command register as shown in Table 1. The current sinks in this design each consists of a single common source NMOS transistor with nonlinear output characteristic, which gate voltage is controlled by a 7-bit digital-to-analog converter. The stimulation current amplitude information is stored in the data register. The most significant advantage of this stimulation scheme is very small chip area consumption compared to the usual current stirring DAC configuration that needs 2^n

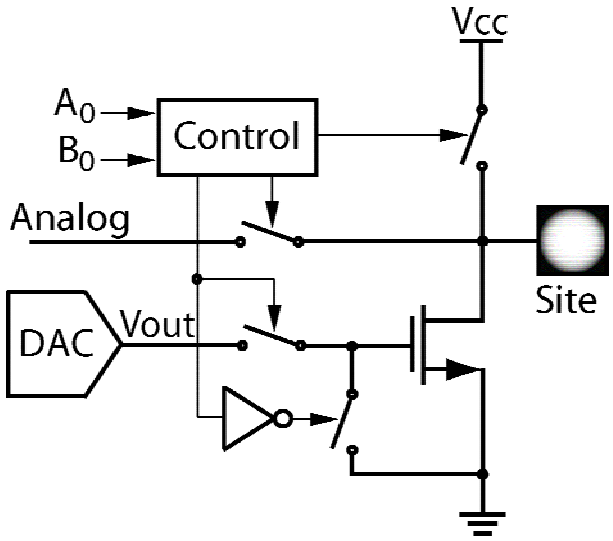


Fig. 9: The site driver circuit

TABLE 1. SITE CONTROL BITS

A	B	Site Status
0	0	High Z
0	1	V_{CC}
1	0	Sink
1	1	Analog

MOS transistors to achieve n-bit resolution. This issue is very important in a 1024-site stimulating microsystem fabricated in a 3µm technology. This nonlinear current sink provides finer resolution over smaller stimulation currents and coarser control over larger stimulation currents. This is what is needed in a neurophysiology setup where smaller currents are used to interact with only one or a small population of neurons but larger currents are used to stimulate bundles or large populations of neurons and small variations in the stimulating current do not make much difference. Basically, from a neurophysiological point of view, we have used the chip area in a much more efficient way. The uses of the common analog line have been described in previous reports and will not be repeated here.

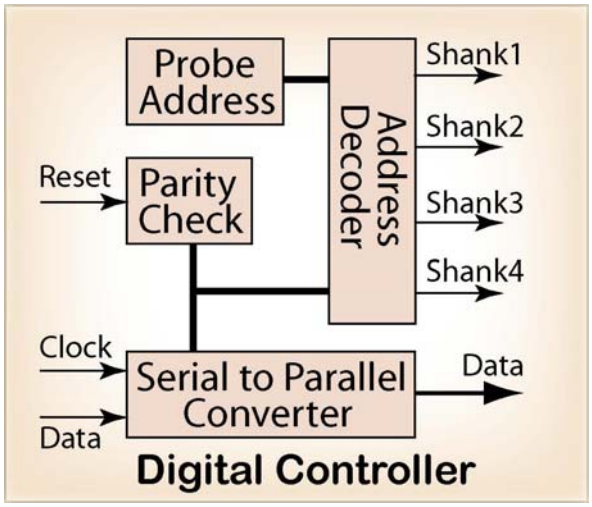


Fig. 10: The digital controller block diagram

The digital controller block is shown in Fig. 10 in more detail. The 18-bit serial data-frame size in Interestim-3 is the same as in Interestim-2; however, the data-frame contents are quite different. Figure 11 shows the Interestim-3 serial data-frame protocol. Each data-frame has 1-byte of amplitude data or site configuration information (D0~D7), 3-bits for internal register address (D8~D10), 6-bits for the probe address (D11~D16), and 1-bit for parity checking (D17). The 6-bit probe address is the first part of the data-frame to be compared with the user-programmed value in the probe address constant-generator block. If the data-frame address matches the probe address, there is a comparator, which activates a 3 to 8 internal address decoder and proceeds by decoding the 3-bit internal register address section and sending the stimulation command or amplitude data to one of the 8 internal registers. Otherwise, the probe just ignores the data-frame and does not change its previous status. The 6-bit probe address is initially set to "00H" by tiny cutting links. These links can be easily cut by the probe station laser prior to connecting the probes in parallel in a 3D assembly. Cutting each link changes the associated address bit from 0 to 1. Therefore, up to 64 probes can be addressed from "00H" to "3FH" and connected in parallel in order to achieve a 1024-site wireless 3D stimulator array. There are a total of 8 separately addressable registers to store site configuration and pulse amplitude information in each probe (two in every shank driver as shown in Fig. 8).

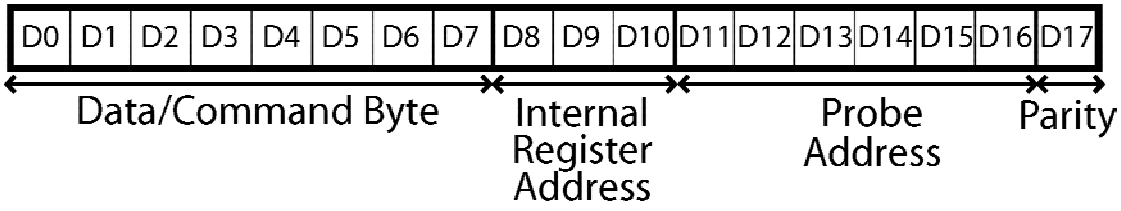


Fig. 11: Interestim-3 data-frame protocol

The reason behind addressing the site configuration command-register and the stimulation amplitude data-register in each shank driver separately is to decrease the amount of data that is needed to be transferred to the implant by the wireless link. In a 1024-site wireless stimulating system with a large number of simultaneous high pulse-rate stimulating channels, it is very important to maximize the efficiency of the information that is being sent across the link; considering limitation in bandwidth due to limited RF carrier frequency. We have realized that in a multi-channel stimulating system the configuration of the stimulating sites changes much more frequently than the stimulating pulse parameters such as amplitude or duration. The researchers usually want the amplitude to be above a minimal threshold level required to trigger an action potential and once above that level, they do not change the pulse amplitude or duration frequently. Therefore, in the Interestim-3 design, once the amplitude data-registers of the shank driver blocks are programmed to the desired levels, the external system has the flexibility to continue by just sending the site configuration information to the command-registers of the shank driver blocks to switch the stimulation currents between desired sites. Considering the fact that the amplitude information has already been stored, the implant knows what current amplitudes should be used for each shank. This scheme, which takes the advantage of the shank driver memory elements, can reduce the amount of data transfer with a certain stimulation rate by 50% unless the application requires different amplitudes for every new stimulating pulse.

The serial to parallel converter block consists of an 18-bit shift register that stores the recovered data, which is clocked in by the recovered clock from the receiver block. The shift register content is latched once it is filled by a data-frame and then the latched data-frame is checked by parity checking block. Finally, the data or command byte within the data-frame is sent to the addressed internal register.

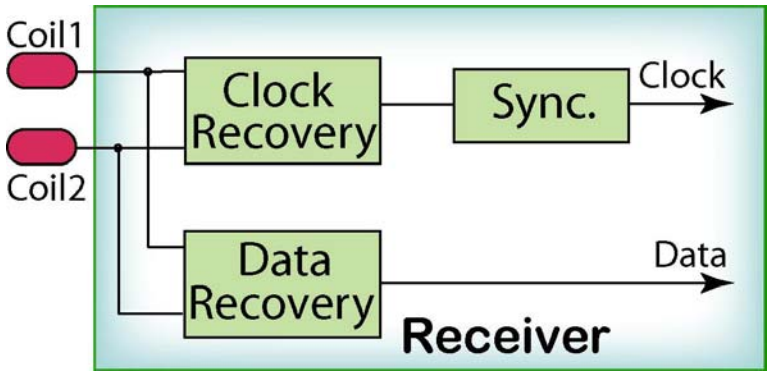


Fig. 12: The receiver block diagram

The receiver block consists of data-recovery, clock-recovery, and a synchronization block as shown in Fig. 12. It inputs the sinusoidal carrier across the tank circuit and recovers clock and data bit-stream for the rest of the chip. There are two versions of this block among the Interestim-3 probes. The first version has a ring oscillator and the ASK demodulator circuits as clock-recovery and data recovery blocks, respectively, similar to what has been used in Interestim-1 and 2. These blocks and their

measurement results have been reported previously. The second version takes the advantage of a cross coupled comparator for clock-recovery and FSK demodulator for data-recovery blocks. The cross coupled comparator, shown in Fig. 13, does not consume any static power and has built-in hysteresis, which is twice the PMOS threshold voltage and helps in rejecting undesirable noise and artifacts. Its cross coupled positive feedback helps to produce a sharp square clock waveform, which is required for precise FSK data demodulation. The FSK data recovery block uses a novel FSK data transfer protocol to achieve data rates above 1Mbps with a 4MHz carrier and has been described in [1]. The synchronization block is only present in the ASK receiver version and slows down the recovered clock to synchronize it with the recovered data bit-stream.

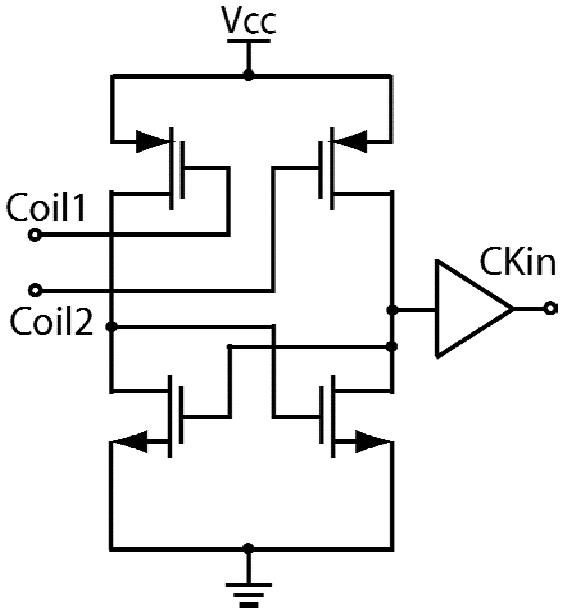


Fig. 13: The cross-coupled comparator used for clock recovery.

Figure 14 shows the power supply block, which generates a regulated 5V V_{CC} for the probe internal circuitry and a regulated 10V V_{DD} for the stimulating site drivers. The distributed power supply scheme which is followed by including a power supply block on every probe has several advantages over a central power supply for the entire 1024-site wireless stimulator system:

1. Each Interestim-3 probe is a self sufficient 2D stimulating array and can be used either individually or in parallel to other similar probes.
2. The power supply output current capability of the 3D system scales by the number of Interestim-3 probes that are used in parallel without any unutilized overhead.
3. Less leakage current through substrate due to lower current levels in each power supply.
4. Better heat dissipation by distributing the high current components across all of the probes.

5. More homogeneous power distribution and less voltage drop due to resistive parasitics.

The power supply block also includes a CMOS full-wave rectifier, which has been described in [2] and a power-on reset block, which activates the probe reset line at the startup and releases it after 25ms when all of the transient voltages have passed and the digital circuits are stabilized.

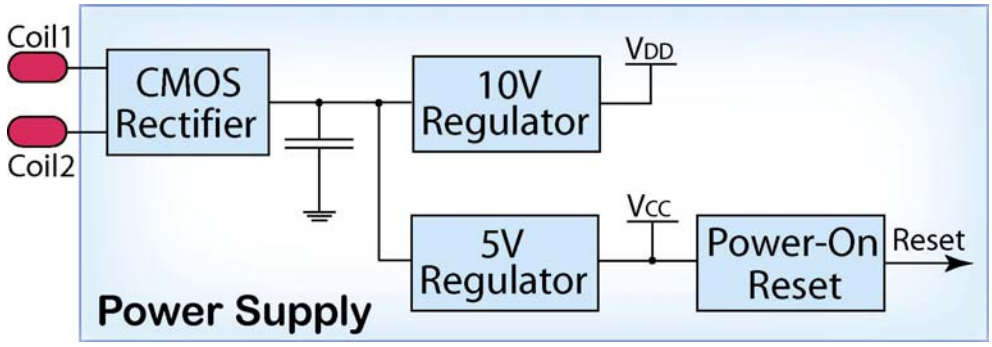


Fig. 14: The power supply block diagram

Interestim-3 Layout:

Interestim-3 probes were laid out in two versions in the University of Michigan 3µm, 1-metal, 2-poly, BiCMOS process. Figure 15 shows the first probe design superimposed with its back-end floor planning. Some of the specifications of this 16-site wireless addressable stimulating probe are summarized in Table 2. Coil1 and Coil2 are two big pads on the sides of the probe, which indicate the location of tank circuit contact nodes as shown in Fig. 7. This 2D-probe has been designed with several micromachined features, such as the spacer trenches near the edges of the back-end circuitry, which allow us to mount it on a platform in a 3D-array structure.

The large feature size (3µm) and only 1 metal layer of the UM BiCMOS process have enlarged the size of the back-end circuitry of the Interestim-3 probes despite our effort to simplify and shrink the size of our circuits with novel methods such as using only a single NMOS for the current sinks. In order to solve this problem and reduce the back-end height of the final 2D or 3D-array for some of the CNS applications such as cortical implants, where the implant aspect ratio should be low, we designed a second version of the probe with flexible shallow boron-dopped silicon ribbons connecting the back-end circuitry to the shanks. The back-end of this probe, which is shown in Fig. 16, can be bent in right angle in order to reduce the height of the probe back-end from 6.4mm to 1.5mm. Table 3 summarized the specifications of this probe.

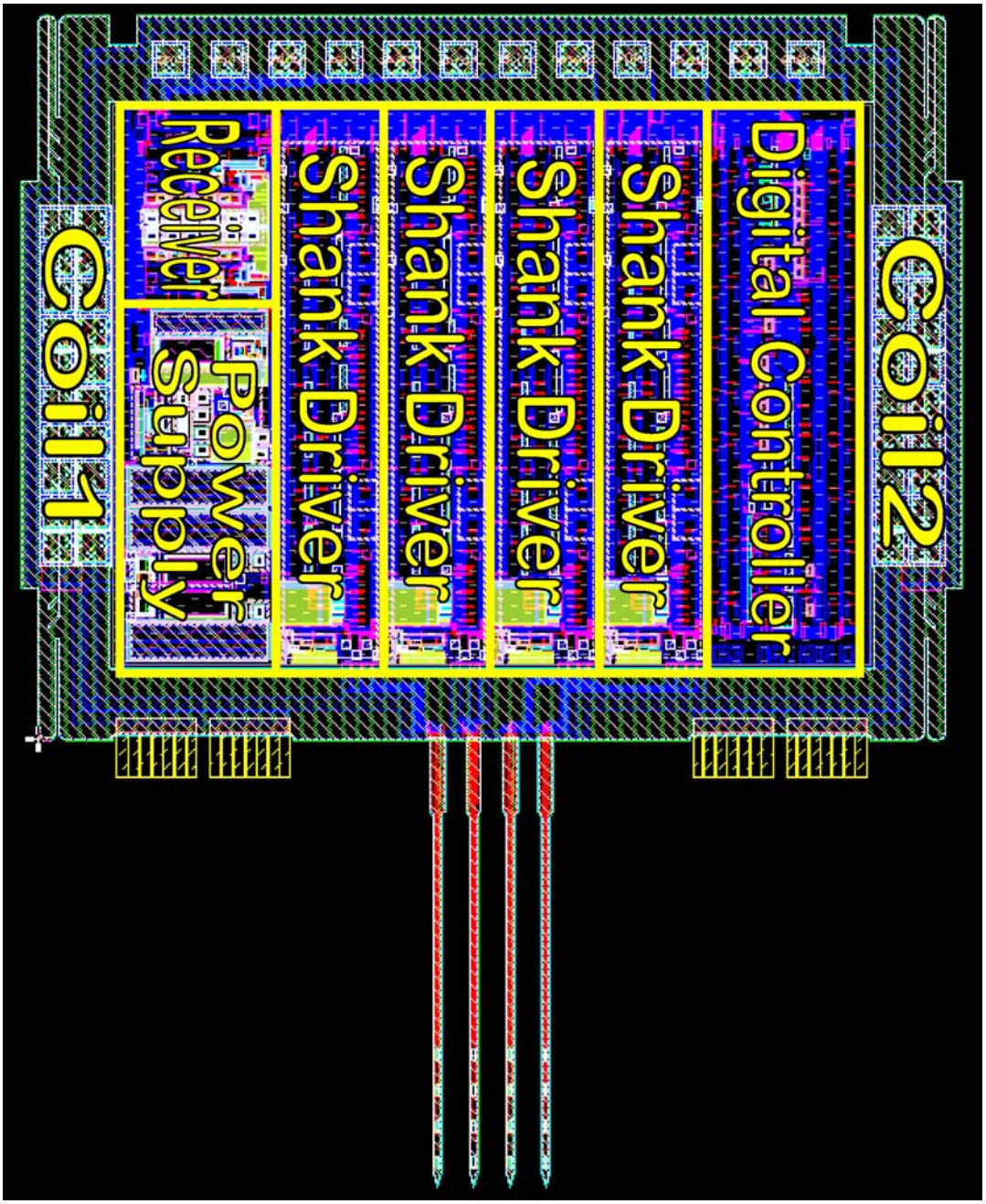


Fig. 15: The Interestim-3 probe-1 layout

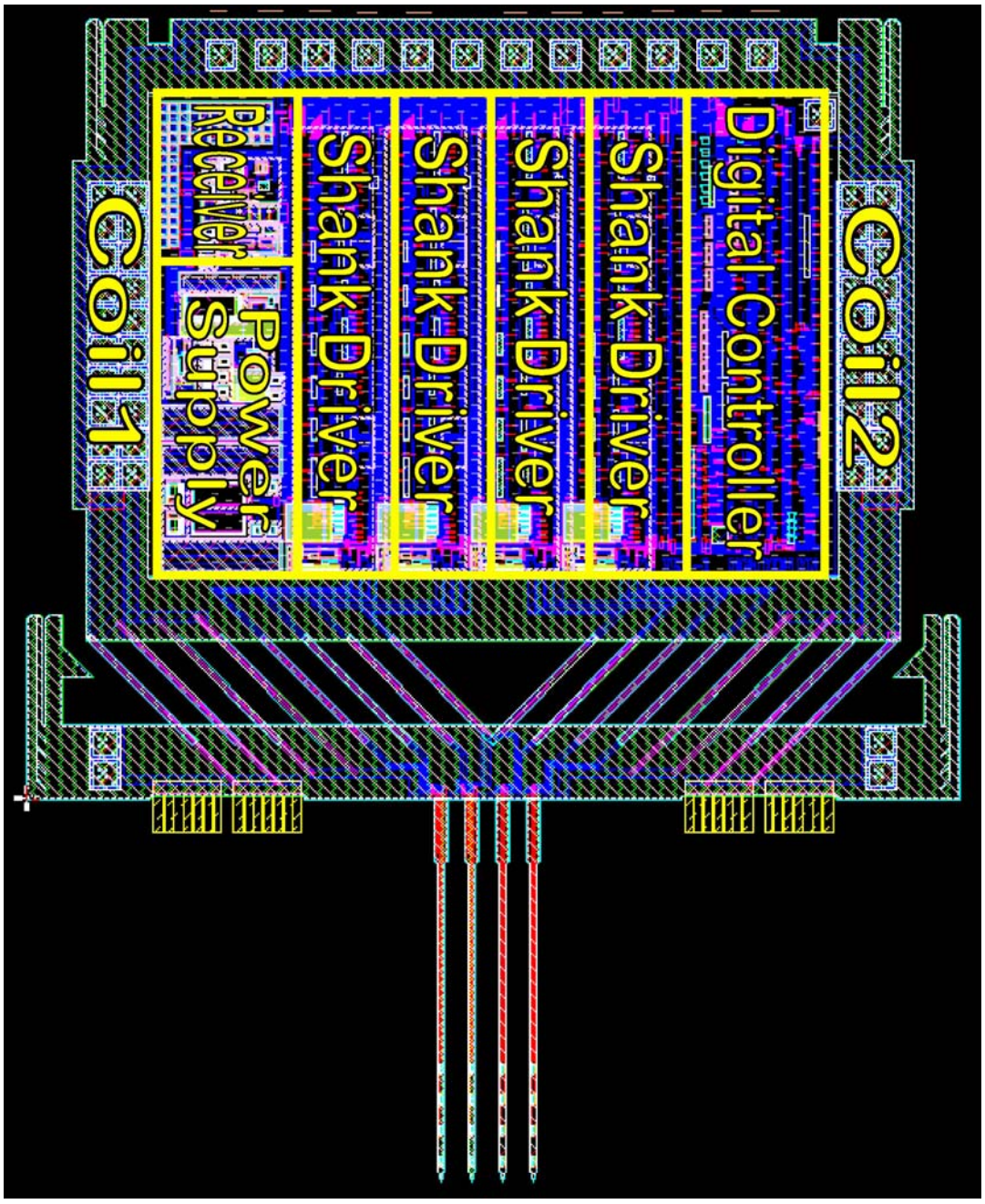


Fig. 16: The Interestim-3 probe-2 layout

TABLE 2: INTERESTIM-3
PROBE-1 SPECIFICATIONS

Outer Boundary	6.5mm × 5.4mm
Back End	6.5mm × 5.0mm
Shank Size	3.1mm × 60μm
Shank Spacing	250μm
Site Area	181μm^2
Bending Back-End	No
Transistors	4200

TABLE 3. INTERESTIM-3
PROBE-2 SPECIFICATIONS

Outer Boundary	7.5mm × 6.4mm
Back End	6.8mm × 5.0mm
Shank Size	3.1mm × 60μm
Shank Spacing	250μm
Site Area	181μm^2
Bending Back-End	Yes
Transistors	4200

4. Conclusions

During the past quarter, work has concentrated in three areas. We have designed and had fabricated at MOSIS a two-channel sixteen-site version of the active probe, STIM-2. This chip contains improved DAC current drivers as well as full self-test circuitry. The probe was returned from MOSIS and is currently in test. The digital input circuit blocks, the DAC circuitry, the anodic bias generator, and the associated self-test circuitry is all fully functional. A detailed comparison of the measured performance with the design simulations is underway. We have also designed a new four-channel 32-site version of STIM-2/-3. This probe has new DAC circuits which are considerably smaller than their predecessors at the cost of some absolute accuracy in the current settings. These probes have been realized in both two-dimensional acute and three-dimensional chronic (platform) versions. To minimize the height of the probes above the platform, we are experimenting with fold-down gold beams in place of silicon cables. The silicon cables have the advantage of being fully insulated on-chip but cannot bend through sharp angles without breaking. The gold beams can be bent at right angles and hence can be shorter and more robust but at the expense of being subject to leakage. However, in a platform situation, these beams will be inside the protective cap and thus not exposed to extracellular fluids. They can also be potted in silicone so that leakage is not expected to be a problem, especially in stimulating situations. Full results from the MOSIS chip and initial results from the STIM-2/-3 probes should be available next term.

We have also designed a two-channel 16-site active stimulating probe with an on-chip wireless link. This probe is thus completely self-contained, including current drivers, input circuitry, power generation, and wireless interface. If wired, the probe can

be operated over a two-wire line. The probe is organized as four four-site shanks. Sites can be programmed as high-impedance, driven to VCC, operated in current sinking mode, or tied to an analog access line. The probe uses an 18b input control word. Probe addresses in multi-probe configurations are set by laser trimming of links. The wireless interface uses an FSK data recovery block that achieves data rates above 1Mbps from the 4MHz carrier. The power block uses a CMOS full-wave rectifier with power-on-reset for the input circuitry. A fold-down version of this probe is included to minimize the height of the structure above the cortex. The shanks are 3.1mm long by 60µm wide spaced 250µm apart. These probes should be realized before the end of the year.

References:

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